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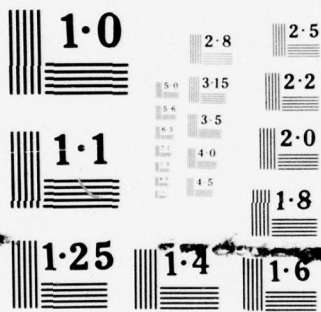
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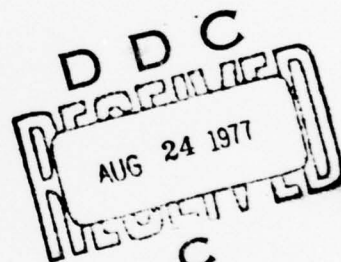
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GEOMETRY AND FUNCTION DEFINITION FOR DISCRETE ANALYSIS  
AND ITS RELATIONSHIP TO THE DESIGN DATA BASE

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August 1, 1977

Technical Report No. 2

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Points, curves, surfaces, and solids in a hierarchical manner. It recognizes that geometric definition is only a part, albeit a fundamental part, of the structural system definition. The geometric components are used as a reference geometry, upon which the user may define loading patterns, kinematic boundary conditions, material property variation and so on. It is in linking these items together with the geometry that a structural analysis becomes feasible.

In presenting and discussing the data base requirement for a structural analysis in a consistent manner, the designer of a CAD system is presented with basic data requirements to be included in his data base design.



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## ABSTRACT

The purpose of this paper is to discuss data requirements for structural analysis, in order to clarify its dependence on the design process as a whole.

The model generation capabilities of a state-of-the-art structural analysis system (GIFTS 4), heavily oriented towards pre- and post-processing and computer graphics, is presented. The system is capable of generating points, curves, surfaces, and solids in a hierarchical manner. It recognizes that geometric definition is only a part, albeit a fundamental part, of the structural system definition. The geometric components are used as a reference geometry, upon which the user may define loading patterns, kinematic boundary conditions, material property variation and so on. It is in linking these items together with the geometry that a structural analysis becomes feasible.

In presenting and discussing the data base requirement for a structural analysis in a consistent manner, the designer of a CAD system is presented with basic data requirements to be included in his data base design.



## I. INTRODUCTION

The paper describes a geometrical definition scheme used in the GIFTS 4 program, a structural analysis package. The scheme is based on a hierarchical representation of geometrical entities: points, curves, surfaces, and solid chunks.<sup>1</sup>

While primarily oriented towards surface definition in this particular structural package, the interface between discipline-oriented packages such as GIFTS and similar packages in other disciplines, such as hydrodynamics, heat transfer, and numerical control is discussed. The lack of a common data base is in a way regrettable, but also understandable. The various disciplines are at different stages of development, in which different mathematical tools are used. Difficulty exists within each discipline in defining the data needed for the analysis, and the most efficient schemes to conduct the analysis and supply the appropriate results. The lack of communication between the various disciplines will be eventually resolved by a centralized computer-aided design effort, such as that of Reference 2. The traditional role of the designer is the hub of the wheel to which all disciplines are connected. In the absence of a well-defined central system for object and problem definition, it is natural that those involved with the day to day analysis, often under pressure, have to take their own initiative and go their own ways.

This is not to be taken as advocating a top-heavy approach resulting in an extensive computer-aided design system, that is unwieldy and inaccessible except to large organizations. The problem is much simpler than that. It is that of the acceptance of a standard for communication, a standard for data storage and conventions so that data and programs may be interchanged with relative ease. It is possible to interface packages that were developed independently at a later stage.

## II. GEOMETRIC HIERARCHY OF DEFINITION IN GIFTS 4

A three-dimensional object, to be designed or analyzed, may be described in terms of a minimum amount of geometric input and some basic logic (see References 1 and 3). A minimum number of points in space, called key points, are chosen and digitized. Next, a number of curves may be generated, using these key points as reference locations. Curves may be straight lines joining two points, circular arcs joining three points, or parametric curves of second and third order. On each curve, GIFTS can generate, automatically, intermediate nodes and line elements (rods, beams). The intermediate nodes need not be equally spaced as will be described later. GIFTS 4 also allows the definition of composite curves constructed out of (up to nine) different segments of the standard types described above. Any curve, including composite lines, is used as an entity in subsequent operations, and is given an alphanumeric identifier.

Once curves have been defined, surface patches may be generated based on them. These patches are generated in a discrete fashion in

the form of internal points and surface elements. The fineness of the grid required for the discrete presentation may be controlled by the user at the time of curve generation. Surface patches are of two basic types, a four-sided patch and a three-sided patch, whose edges may be any of the above curve types. In both cases, the discretization technique generates internal points by blending one edge into the opposite edge or corner. Examples of such patches are given in Figure 1. A number of surface patches may be collected together under a common name to produce a composite patch. Each surface patch, including composite patches, is used as an entity in subsequent operations, and is designated an alpha-numeric identifier by the user.

A new addition, expected by the end of this summer, will utilize previously defined surfaces in order to generate solid chunks. Several types are contemplated. For example, the PRISM4 chunk is a solid piece of continuum bounded by six four-sided grids or patches. The PRISM 3 chunk is a piece bounded by five sides, three of which are rectangular and two triangular. A tetrahedron (TETR4) solid chunk is a four-sided piece of continuum bounded by four three-sided patches (see Figure 2).

It may be argued that the generation of geometrical figures in such a manner is basically a computer-aided design problem and should perhaps be incorporated in a computer-aided design system, rather than in a structural analysis program. Indeed, such information may and should eventually, be obtained from a computer-aided design package. However, structural analysts need a certain amount of sophistication in the definition of geometry, and are apt to resort to their own means to produce such definitions in a readily accessible form so as to be usable in analysis programs. It is important to note that the geometric definition of the surface patches, the curves and the solid chunks, is not by itself sufficient for the conduct of the structural analysis. The structural analysis analyst must perform additional operations, based on the geometrical definition, the most important of which is the discretization of lines, patches and chunks by the introduction of grids, containing internal nodes and line, surface, and solid elements.

The fineness of the grid is an important factor in determining the accuracy of analysis. It will be shown in this report that there are simple ways of varying the fineness of the grid from one area to another in order to produce accurate modeling where needed, a matter very much dependent on the judgment and experience of the structural analyst.

Furthermore, surfaces and solids are the basic geometric entities on which loads and temperatures may be defined. In the process of discretization, simple loading patterns, such as a pressure on a surface, or a distributed load along an edge, have to be translated into hundreds of individual load vectors applied to the nodes of the structural grid. This is a process that can only be performed if the geometric properties of the surfaces and the curves are known and available explicitly to the structural analyst, who is concerned with the discretization of the load. The GIFTS 4 program preserves the logic of the model and allows the user to address the individual geometric elements in defining his loads. For example, he may apply distributed loads to lines, pressures to surfaces

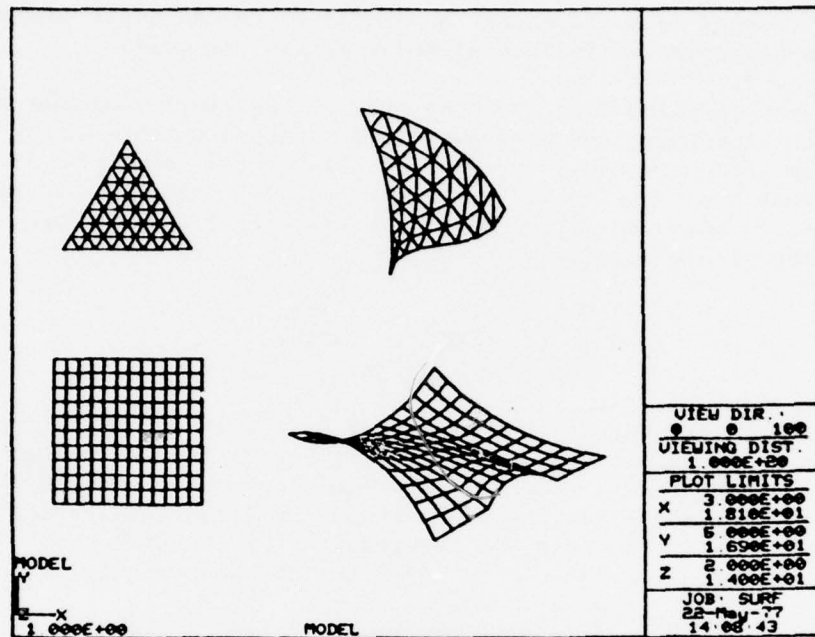


Figure 1. Generation of 3 and 4-sided surface patches with arbitrary side shapes

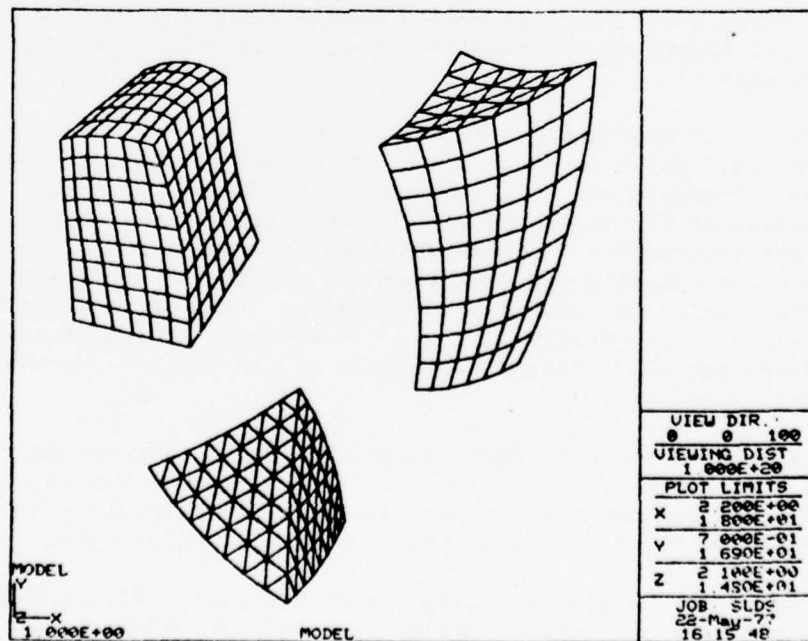


Figure 2. Solid Chunk Generation using GIFTS 4

and body forces to solid chunks as easily as he can apply concentrated loads to key nodes or individual nodes within his grid.

From this discussion, we hope that we have explained the motivation behind the incorporation of geometric definition schemes and a structural data base in a structural analysis program. It is also clear that such a data base has to be available to the analyst, via powerful user-oriented manipulation commands, which allow him to control the accuracy and efficiency of his solution.

### III. LOAD APPLICATION

As mentioned before, the geometric definition of the structure is only the first step towards the design. Structures are designed to support certain loads, and it is the function of the structural analyst to investigate the efficiency with which the structure carries such a load. In order to do this, he may resort, for example, to the finite element method, the method upon which the GIFTS 4 package is built.

Loads may be defined with a minimum number of specifications in the same way that a geometric surface can be represented by a minimum number of coordinates and logical connections. It is useful that the user may reference the surface definition in creating his loads. For example, the user may specify the distributed load values at the two ends of a curve and let the program discretize the pressure into individual loads automatically placed at the individual points.

A curve may be a straight line, a circular arc, a parametric curve, or a composite line. GIFTS computes the pressure at an internal node using first order Lagrange interpolation functions (Ref. 4 and 5). The developed length of the polygonized curve is used as a length parameter (see Figure 3).

The same approach can be applied to surface patches. For example, a four-sided patch (see Figure 4) is defined in terms of four boundary curves. Pressure values are given in this case at the four corner nodes. The values of the intermediate pressures are derived on the basis of a bilinear interpolation scheme which establishes a  $2 \times 2$  square and maps it onto the actual shape of the patch. Since the borders of the patch are arbitrarily shaped and blended by the GIFTS patch generation scheme into a series of parallel curves, the bilinear interpolation is based on the developed chord length along each of the two intersecting lines at a particular point.

The loads per unit area can be deduced, therefore, at each one of the individual nodes. Considering a surface elements, one can compute the resultant forces on its corners, using a kinematically consistent load method (Ref. 6), and assign them to the surrounding nodes.

Loads may be applied along one of the global directions  $x$ ,  $y$ ,  $z$ , in which case the pressure values at the patch corners are interpreted as the loads per unit surface area, acting in the specified directions.



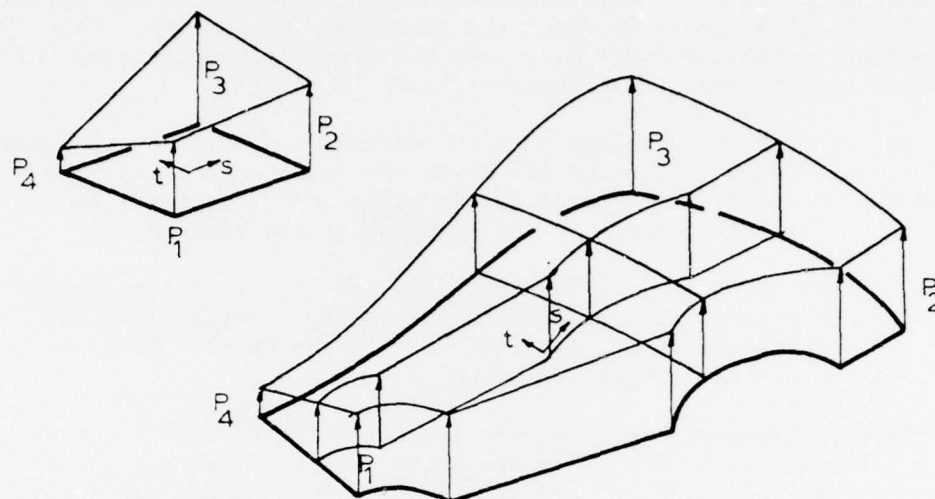


Figure 3. Interpolation of linearly distributed load along arbitrary curve.

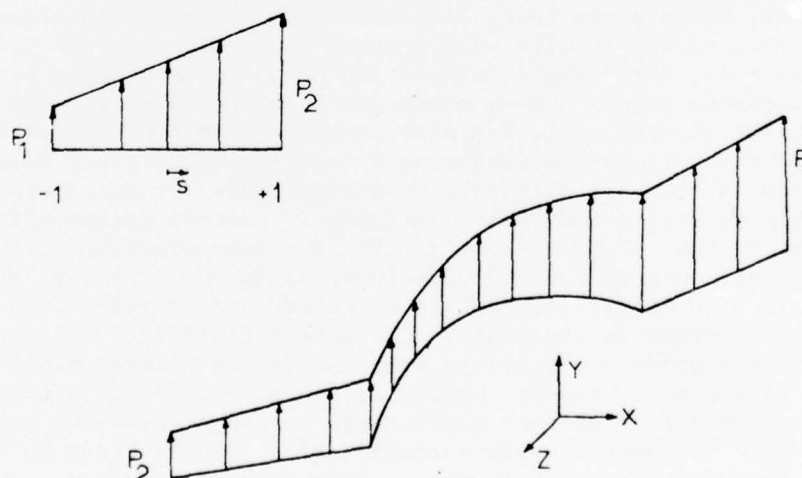


Figure 4. Interpolation of bilinear load distribution over arbitrary surface.

Loads may also be applied as pressures perpendicular to the surface. In such a case, there is a need to determine the direction of the normal to the surface at the point at which the pressures are applied. This presents no particular difficulty, and the normal vector is computed on the basis of two local chord segments.

Special load applications in GIFTS include hydrostatic pressures, due to liquid heads, which may not cover the patch entirely. Such a loading occurs often in marine applications and, therefore, is considered a useful addition to the commands of the program.

The above methods of load description and discretization may be expanded to higher order variations of pressures, such as, for example, quadratic and cubic pressure distributions on the patch. Such extensions will be incorporated if there is demand for them.

Figure 5 represents a patch generated from complex edge curves. Figure 6 shows the results of an automatic pressure load discretization by one of the GIFTS modules. Figures 7 and 8 represent a fictitious ship hull generated and displayed by the GIFTS program in order to demonstrate GIFTS' ability to generate complex surfaces.

#### IV. EFFECT OF MESH SPACING ON ACCURACY

Once a structure has been defined, a mathematical model is required in order to perform a finite element analysis. The accuracy of such an analysis depends on many factors. The word accuracy itself here needs clarification since it usually is not constant within the model itself.

It is a well-established fact that the finite element method is convergent, which means that, by subdividing the model into smaller and smaller pieces, the results will improve (see Ref. 7). The speed of convergence is, for example, a function of the element type being used. Simple elements have a slower convergence rate than more complex higher order elements. It has also been observed that the element shape is an important factor in obtaining a numerically accurate solution. This claim is somewhat difficult to assess since element shapes cannot be completely uncoupled from other variables. Another factor affecting accuracy is that of grid density. It is common practice to put more nodes and elements at a particular location in the structure where, for example, a high stress gradient is expected, and to reduce the density of nodes and elements in areas where the stress field is fairly constant. Such variable grids are possible with the finite element method and have a great advantage. However, more study is needed in order to determine precisely the effect of such a procedure on the accuracy of the analysis as a whole. Furthermore, the variation of a grid in order to obtain higher accuracy assumes that the analyst knows, in advance, where stress concentrations are, and that he is willing to sacrifice the accuracy in other parts of the structure in favor of the local area.

A number of student projects were conducted at the University of Arizona in order to study the efficiency of grid configuration. The

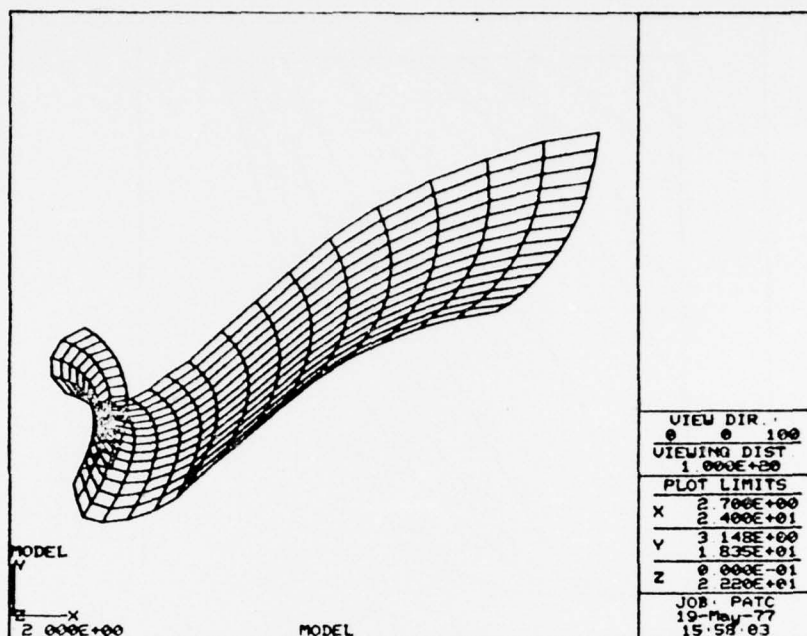


Figure 5. Surface patch generated from four arbitrarily shaped sides.

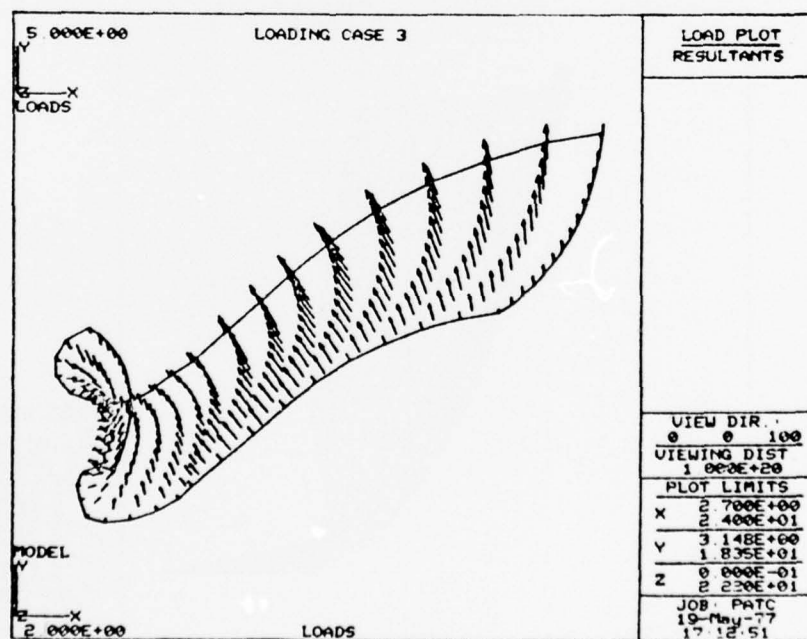


Figure 6. Automatic generation and discretization of bilinearly varying pressure load on arbitrarily four-sided grid.

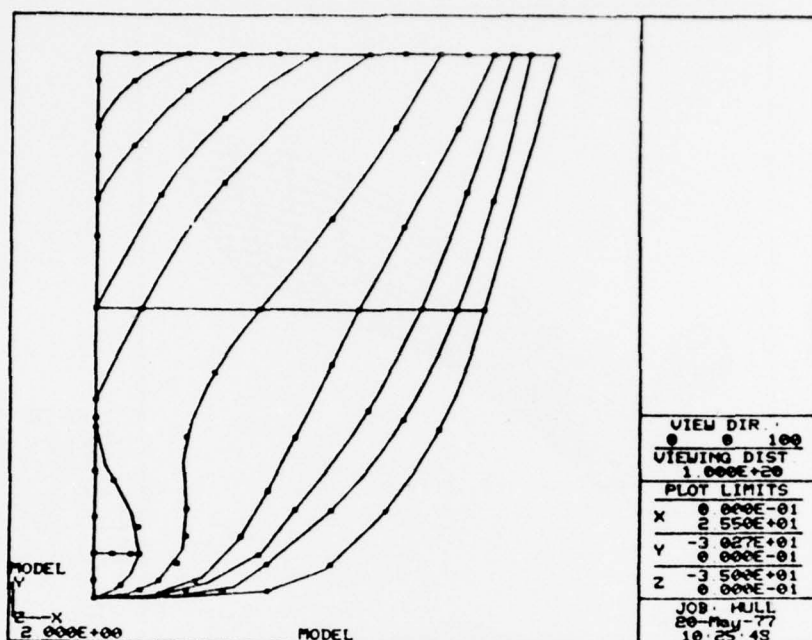


Figure 7. Head on view of part of ship side shell.

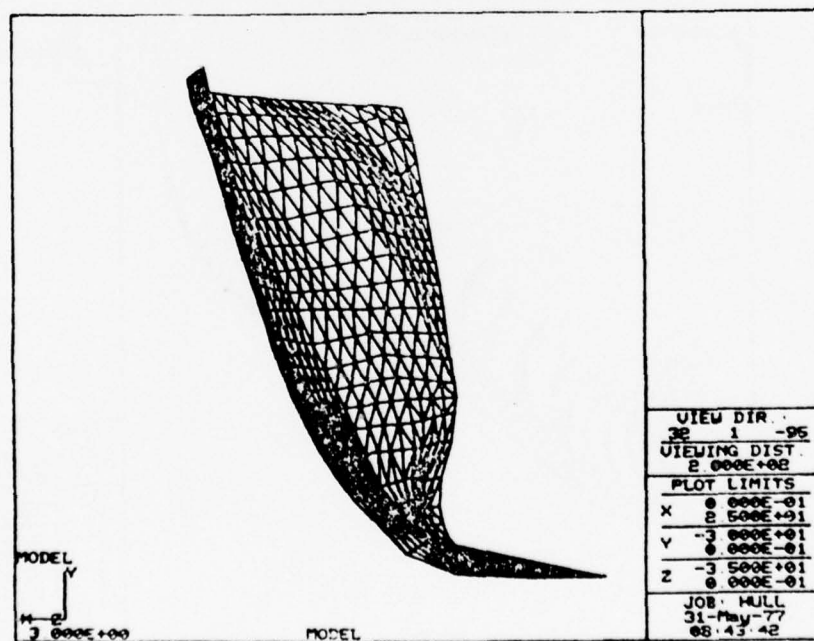


Figure 8. Isometric view of ship side shell.



problem of stress concentration around a circular hole in a square membrane plate was solved using an increasingly larger number of equally spaced nodes. Alternatively, a feature of the GIFTS program in which the grid is biased to increase the point and element density at the point of interest was employed (see Figure 9).

Table 1 gives the results of parametric studies which show the striking superiority and accuracy of grid biasing as compared to the uniform refinement over the plate. In estimating the accuracy, the von-Mises stress value at the centroid of the (isoparametric quadrilateral) element nearest the stress concentration was compared to the classical solution, including the correction for the finite plate size, at the point of maximum stress concentration. Although some questions still remain unanswered, such as the accuracy of the exact solution, and whether extreme bias of mesh size produces numerical errors, it is, in our opinion, clear that using biased simple grids is the most efficient method for accuracy enhancement. It is recommended that an analysis be performed in two stages, using a simple grid with a small number of nodes and elements. The first analysis serves to indicate areas of interest, while the second is aimed at obtaining more accurate results at these areas. It is also clear that more research should be conducted in order to produce simple modelling guidelines and clarify the above questions.

#### V. AUTOMATIC GENERATION OF INTERNAL POINTS WITH BIAS

Two types of bias are possible in the GIFTS System. For the time being they cannot be combined. The "center bias" results in automatically generated points being closer towards the center of the curve for a positive bias and towards both ends of the curve for a negative one. For "end bias," the points are closer towards the second endpoint in the curve (positive bias) or towards the first (negative bias).

From a user's point of view, the most convenient way of specifying bias is to give the ratio between the longest and the shortest segment in the form of a percentage. In this manner, a zero bias means equal segments, a bias of 100 indicates the largest is twice as long as the shortest.

For straight lines and circular arc segments a simple arithmetic progression can be established from which one can calculate the length of the first and the last segments and the increments as one moves from one segment to the next. This scheme is indeed utilized in the program for its simplicity and accuracy. In parametric curves, however, the position of the intermediate geometric reference points, necessary to generate the parametric curve, may result in non-equal length for the various segments, even if the parameter values corresponding to the intermediate points are equally spaced. A method must be derived, therefore, from which the values of these parameters can be selected so as to produce the correct ratio between the longest and the shortest segments regardless of the position of the intermediate points. The following

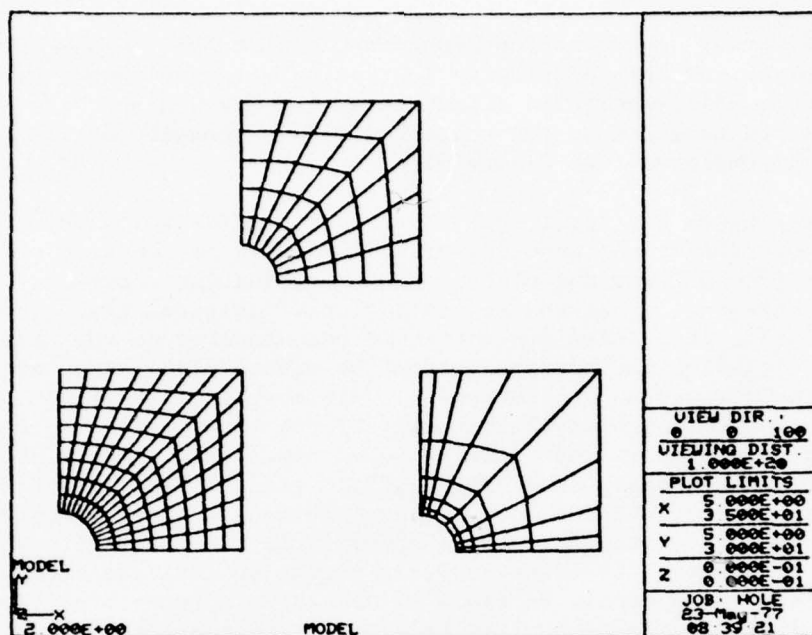


Figure 9. Stress concentration around a hole, alternative modelling approaches to increase accuracy.

NO. OF NODES	EST. COST MULTIPLIER	ERROR%
40	1.000	226
60	1.884	15.6
84	3.327	10.5
112	5.209	8.0
144	7.975	6.0

TABLE 1

LENGTH RATIO(BIAS)	ERROR%
1	22.60
2	13.10
3	8.17
4	5.00
5	3.00
6	1.40
7	0.27
80	2.20

section describes the scheme currently utilized, which is successful as long as the intermediate points are approximately equally spaced. It may fail in situations where the intermediate points are unreasonably chosen, particularly if they produce, *ab initio*, a node spacing in conflict with the one specified by the user. The following discussion will clarify this point, and describe the method employed to achieve biasing.

#### V.1 Effect of Center Point Position on the Spacing of Internal Nodes

Assume a straight line, of length  $2L$ , joining two points. It is required that the intermediate nodes be generated such that the spacing may be biased towards one end. It is proposed here that this be done by using a second order parametric interpolation utilizing a fictitious intermediate point on the original line, whose position may be used to control the spacing. The second order Lagrangian interpolation functions are given by:

$$\begin{aligned} f_1 &= -S(1-S)/2, \\ f_2 &= 1 - S^2, \\ f_3 &= S(1+S)/2, \end{aligned} \tag{1}$$

where  $S$  is a parameter varying between  $-1$  and  $+1$ .

From Equation 1, one may derive an interpolation relationship giving the position,  $x$ , of an intermediate point as a function of the parameters. Assuming the coordinates of the first, intermediate, and last points to be  $-L$ ,  $\beta L$ , and  $+L$ , one arrives at:

$$x = -\beta L S^2 + S L + \beta L \tag{2}$$

Figure 10 shows the relationship between equally spaced set of  $S$  parameters and the resulting  $x$  parameters for various values of  $\beta$ . For example, if the intermediate point is the midpoint ( $\beta = 0$ ), the mapping function is a straight line and results in equal spacing. If  $\beta$  is negative, the nodes are closer towards the first point and if  $\beta$  is positive, then the nodes are closer to the second point. Therefore, it seems that by the appropriate choice of  $\beta$ , one can produce and control an end bias and may be indeed able to compute the  $\beta$  value to achieve a particular bias. One must note, however, that if the value of  $\beta$  increases beyond  $0.5$  or is less than  $-0.5$ , that some interpolated values will lie outside the range of  $-L$  to  $+L$ , and will not be acceptable. It is possible to prove this by using Equation 2. The derivative of  $x$  with respect to  $S$  is given by Equation 3 from which one can see that the derivative will become zero at the line end points for values of  $\beta$  outside the range  $-1/2$  to  $+1/2$ .

$$\frac{dx}{dS} = (1 - 2\beta S) L \tag{3}$$

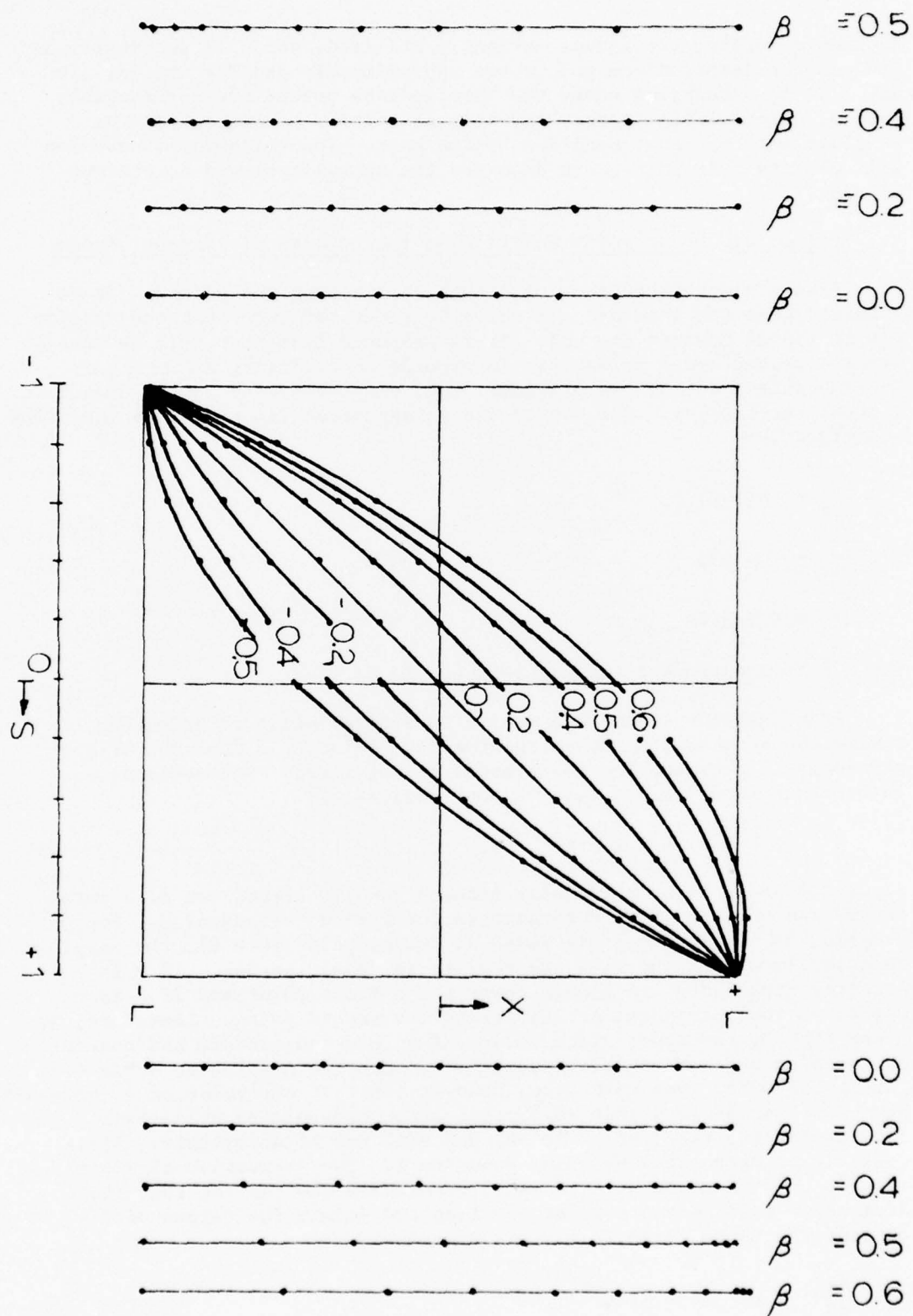


Figure 10. Generation of end biased intermediate nodes.



It remains now to devise a method by which  $\beta$  may be chosen in order to produce a particular ratio of segment length, say B. If we define B as the ratio the length of the first segment to the last segment, then this may be approximated by the ratio between the derivatives at both ends.

$$B \approx \frac{\left. \frac{dx}{dS} \right|_{-1}}{\left. \frac{dx}{dS} \right|_{+1}} \approx \frac{1 + 2\beta}{1 - 2\beta} \quad (4)$$

From which one can calculate the value for  $\beta$  to produce a certain length ratio B:

$$\beta = \frac{(B - 1)}{2(B + 1)} \quad (5)$$

It must be noted, however, that this relationship is approximate since it is based on a continuous approach, rather than discrete. If one wishes to be accurate, a Newton-Raphson procedure has to be used in order to force the ratios to be as specified by the user. The convergence of the procedure, however, cannot be guaranteed for complex curve shapes.

#### V.2 Producing Center Bias on a Straight Line

In order to produce a center bias on a straight segment, we chose a third order parametric representation in which two auxiliary points equally distant from the midpoint of the line are chosen. These coordinates are given by  $-\beta L$  and  $+\beta L$ . By changing the value of  $\beta$ , one should be able to produce and control a center bias. The third order Lagrangian interpolation functions, in this case, are given by:

$$\begin{aligned} f_1 &= (9S^2 - 1)(1 - S)/16 \\ f_2 &= 9(1 - S^2)(1 - 3S)/16 \\ f_3 &= 9(1 - S^2)(1 + 3S)/16 \\ f_4 &= (9S^2 - 1)(1 + S)/16 \end{aligned} \quad (6)$$

From these equations, it is possible to write the coordinate x of an intermediate point on the line as a function of  $\beta$ .

$$x = [(18 - 54\beta)S^3L + (54\beta - 2)SL]/16 \quad (7)$$

The mapping of S into x is shown in Figure 11, where it is seen that if  $\beta$  is chosen to be  $1/3$ , a straight line mapping function is produced, which results in equal spacing. If the auxiliary points are taken further apart ( $\beta > 1/3$ ), a negative end bias is produced and the points are denser towards the ends of the line. Beyond a certain value of  $\beta$ , points are produced outside the original segment, which is undesirable.

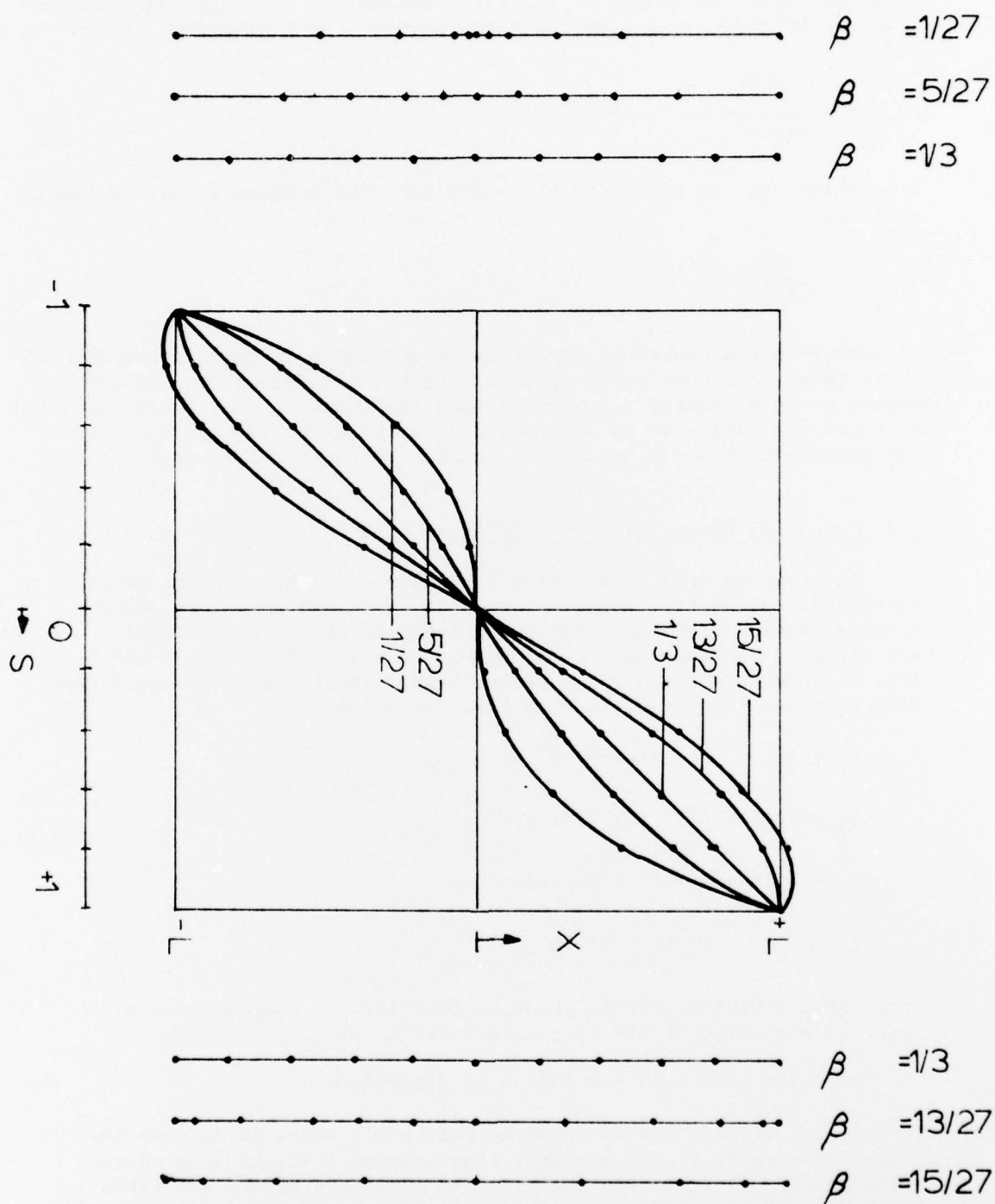


Figure 11. Generation of center-biased intermediate nodes.

On the other hand, if the auxiliary points are taken closer together ( $\beta < 1/3$ ), a positive center bias is produced, whereby the intermediate points are closer towards the midpoint of the line. It also appears that moving the midpoints in that direction is much less sensitive than moving them towards the outside. However, if  $\beta$  is small enough, the curve becomes such that multiple values are possible towards the center of the line, which again should be avoided. In order to compute the limits on  $\beta$  values we use Equation 7 to obtain:

$$\frac{dx}{dS} = \frac{(54 - 162\beta) S^2 L + (54\beta - 2)L}{16} \quad (8)$$

In order for the derivative to become zero at the ends, we have:

$$\left. \frac{dx}{dS} \right|_{\pm 1} = \frac{(52 - 108\beta)L}{16} = 0 \quad (9)$$

which produces  $\beta$  values of  $13/27$ . On the other hand, to investigate the case of the derivative disappearing at the center point, we obtain:

$$\left. \frac{dx}{dS} \right|_0 = \frac{(54\beta - 2)L}{16} = 0 \quad (10)$$

which produces a value for  $\beta$  of  $1/27$ . It appears, therefore, that acceptable  $\beta$  values lie between  $1/27$  and  $13/27$ .

It now remains to find the value for  $\beta$  for which a certain bias,  $B$ , may be produced. From Equation 8 we write:

$$B = \frac{\left. \frac{dx}{dS} \right|_1}{\left. \frac{dx}{dS} \right|_0} = \frac{52 - 108\beta}{54\beta - 2} \quad (11)$$

It is now possible, therefore, to choose the value of  $\beta$  to produce a known bias (length ratio) of  $B$ :

$$\beta = \frac{52 + 2B}{108 + 54B} \quad (12)$$

The remark in the case of end bias applies here also. This is only an approximate method. To obtain exact values for  $\beta$ , an iterative method has to be used, whose convergence is not always guaranteed.

### V.3 Producing Bias on Parametric Curves

The above derivations were based on the idea of producing known end or center bias on a straight line. The generalization to parametric curves follows the same logic, utilizing a two-step procedure.

Figure 12 shows an example of a third order geometric curve generated using four points. It is to be discretized using, for example, an end bias. The parametric equation of the curve is solely determined by the

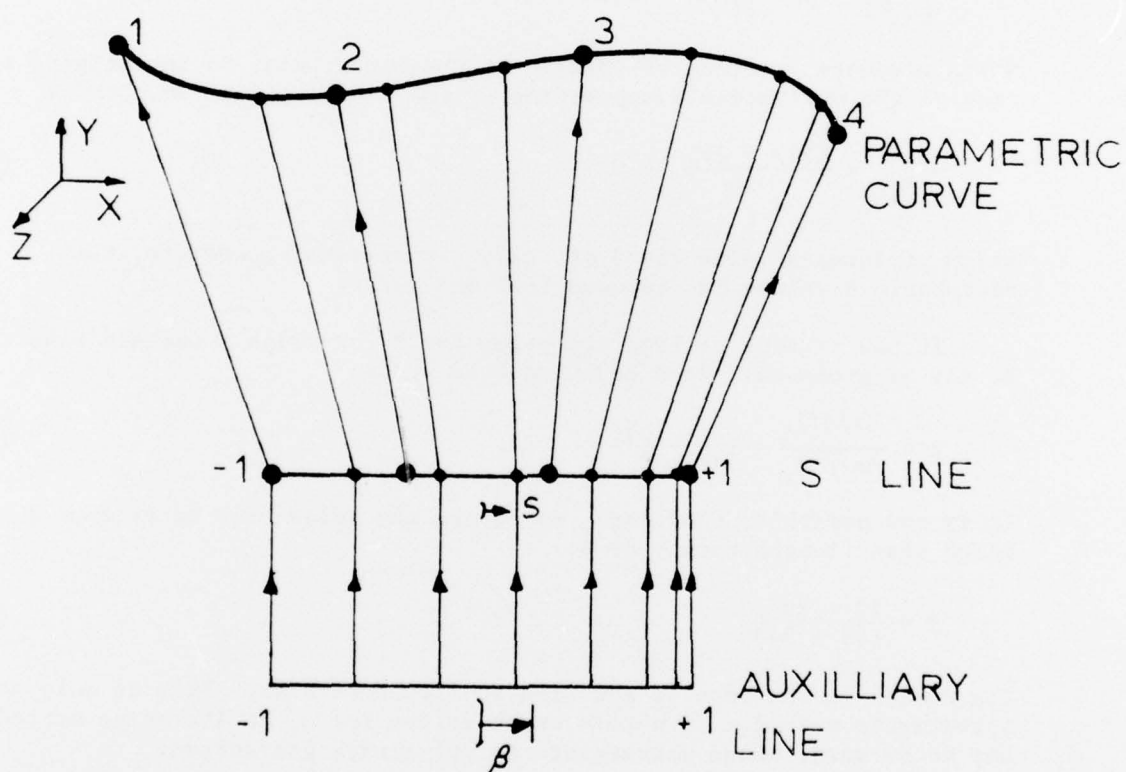


Figure 12. Generation of end-biased intermediate nodes on an arbitrary parametric curve.



position of these four points, the two intermediate points being directly related to  $S$  values of  $-1/3$  and  $+1/3$ , respectively. One constructs a straight line of length two, which maps one to one onto the  $S$  line. A center point on that line is chosen, which may be placed eccentrically by a value of  $\beta$  in order to produce non-uniform spacing on that straight line. It will be assumed that no appreciable distortion results from the definition of the original parametric curve so that the bias ratio of the line produces a sufficiently close bias ratio on the parametric curve. The generated coordinates of the intermediate points on the straight line are then used as parameter values,  $s$ , of points on the parametric curve. An iterative process is necessary here. The ratio of the first and last segments are measured after each step and a Newton-Raphson procedure is used in order to obtain closer values. In the process, care must be taken that  $\beta$  does not depart from allowable limits.

Because of the success of the method of point-biasing in improving one's results without major reconfiguration of the discretized model, we plan to continue improving upon the current capabilities and produce amongst other things, a combined end/center bias to give more flexibility to the user. It would also be desirable to incorporate the actual geometry of the parametric curves in the computation of  $\beta$  so as to provide a non-iterative method.

#### VI. RELATIONSHIP BETWEEN THE STRUCTURAL DESIGN DATA BASE AND MASTER DESIGN DATA BASE

It was necessary, in order to produce a structural analysis system that would completely span the process of analysis, from definition of geometry and loads, to the processing of the final results, to infringe upon the area of computer-aided design insofar as creating geometry definition programs, upon which discretized models are based. It is clear, however, that all or most, of the key information required to construct a model may, and should indeed, be extracted from a master design data base. Not only should geometry be extracted, but also such things as material properties and thicknesses. Such quantities should be stored in the master design data base because they will be used by more than one user. If the structural analysis shows that, for example, certain thicknesses or materials have to be changed, such changes should be communicated back to the master data base so that other users may have access to them.

In essence, we are talking about a distributed data base (8) which is made up of a central design data base and a number of special purpose ones. We are confronted with many problems, including the integrity of such data bases, so that for example, a change in the thickness by a structural engineer does not conflict with a change introduced by the heat transfer engineer. It is beyond the scope of this paper to go into this in detail, since the problems are complex and belong naturally enough in the realm of computer science. On the other hand, if the problem

of design of such a system is left entirely to people in the computer science area, the result may be unwieldy and encumbered by lack of appreciation for the engineering aspects involved in the computer-aided design.

It is obvious that information such as key point locations, and the boundary lines and surface patches should be available from the computer-aided design group, in such a way as to be acceptable to the discretization program. We also need scantlings and thicknesses and material properties. In addition, we need to extract from the master data base the loads under which the structure is to be analyzed.

Files generated locally, such as those containing the coordinates of internal points specifically computed in order to obtain numerical answers should not, in any way, be communicated back to, or maintained by the design data base. The loads, on the other hand, are computed for example, by the hydrodynamicist and may be passed directly to the structural engineer, possibly via the master data base. It appears that the following rules should determine the relationships between the various data bases:

1. There is a central design data base and a number of specialized data bases.
2. Data contained in the master data base should include local master data base information required for the management of the project (but not necessarily available to any of the individual users). It should also comprise all data shared by more than one user. Such data should be accessible to those involved in the individual disciplines.
3. Each specialized data base should contain those items extracted from the master data base, plus additional local files that are necessary to conduct relevant computations. If the results of a computation should specify a change to one of the items in the master data base, the new value should be communicated to the master data base.
4. Any changes introduced from the special data base to the master data base should be subject to approval by the central design team. As soon as a change is accepted and incorporated in the master data base, the specialized data bases should be immediately notified of the effect of this on local activities, some of which may be already in progress. If a change triggered by a special group is in conflict with a proposed change from another group, automatic communication must be established by the system, prompting the individuals concerned to resolve their conflict.

The discussion in this section is bound to be over-simplified. It is not meant as a comprehensive solution to the problem, but rather as a reinforcement of current thoughts on a difficult problem being tackled at the moment by many capable groups. By attempting to portray the problem from a structural engineer's point of view, we hope to have made the designer of a computer-aided design system and the associated

centralized data base aware of a specialized point of view that may benefit him in producing an efficient system.

It is important to note here that reduction of system size and complexity is extremely important, affecting its operational efficiency. One has to resist the tendency to produce systems in which great amounts of sophistication are an investment without a visible return.

## VII. CONCLUSION

The paper describes a structural analysis program which in some ways may appear to infringe upon computer-aided design. This infringement is based on necessity rather than over-ambition. It is hoped that such infringement may be reduced in the future. This can only be the result of a satisfactory resolution of the complex problem of computer-aided design.

The paper includes a description of specialized geometry generation techniques which are useful in the performance of accurate structural analysis. The purpose is to make the computer-aided design specialist aware of particular needs that the structural analyst may have in the area of computer-aided analysis.

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